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COUPLING GLERL WITH RAMS TO STUDY SURFACE WIND WAVE EFFECTS ON AIR-SEA FLUXES IN CHESAPEAKE BAY

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1. INTRODUCTION

Surface wind waves play an important role in the air-sea transfer of momentum, mass and heat. Several field experiments reported that wave age, C_p/u_* (C_p is the wave phase velocity at spectral peak), is an important parameter for determining air-sea drag coefficient, Cd, or surface roughness length, z_0 (Donelan 1990; Geernaert et al. 1987; Smith et al. 1992; Lin 2000; Lin et al. 2002). Other theoretical or modeling studies (Janssen 1989, 1991) also suggested that wave age is a controlling factor for determining z_0. Wave breaking generates air bubbles and significantly enhances gas transfer over water surface (Loewen 2002). Most recently, Deane and Stokes (2002) found that the size distribution of the entrained bubbles is critical to the way that air and sea interacts.

Meso-scale meteorology models currently used to predict surface winds and air-sea fluxes do not include a sea state dependent surface roughness length over water surface. Fully coupling a wave model with a meteorology model seems to be the best way to address the surface wave effects on the air-sea fluxes of momentum, mass and heat. In a coupled wave/atmosphere modeling study, Doyle (1995) found that young wind seas significant increase the surface wind stress. Desjardins et al. (2000) reported a 10% surface wind and 30% air-sea flux difference between the coupled and uncoupled model runs in the Atlantic Ocean Hurricanes. In the same study, Lalbeharry et al. (2000) found that the significant wave heights show better agreement with the buoy observations. These coupling studies were conducted in the open ocean where young wave seas are present occasionally but not dominated. In a shallow, (semi-) enclosed coastal environment, such as Chesapeake Bay (CB), fetch-limited young wind sea dominate the ocean surface wind waves, and the wave effects on the air-sea fluxes are expected to reach the maximum. The objective of this paper is to present a full coupled modeling study on wave effects on air-sea fluxes in the CB, an entirely fetch limited coastal environment with dominated young wind seas.

In summer 1998, a joint tower experiment was carried out by University of Maryland Center for Environmental Science (UMCES) Horn Point Laboratory (HPL), and Air Resources Laboratory (ARL), NOAA. A unique data set of air-sea fluxes and surface wind waves was collected in mid-CB from July 19-28, under low to moderate wind conditions. Lin et al. (2002) described the tower setup, data analysis, modeling results of the experiment. The analyzed data show that neutral drag coefficients depend upon both wind speed and wave age. They are better correlated to wave age than wind speed. Under light winds, the neutral drag coefficients increase with decreasing wind speed and have values much higher than those for relatively higher wind speeds. At higher wind speeds, neutral drag coefficients increase with increasing wind speed. Regardless of wind speed, neutral drag coefficients always decrease with increasing wave age. A parametric, deep water numerical wave model, Great Lakes Environmental Research Laboratory wave model (GLERL), developed by Donelan (1977) is modified to include a sea state dependent form drag and a reference system moving with the waves. It is used to study the wave effects on momentum transfer across the air water interface. The relationship between modeled drag coefficient and modeled wave age agreed well with the relationship derived from the data. GLERL model predicts total drag as a byproduct of the wave calculation and is computationally fast. It is shown to be a good tool for coupling with meso-scale atmospheric models to effect improved, fully coupled

estimates of winds, waves, and air-sea fluxes of momentum and heat.

In this paper, we present a next-step study for the tower experiment. The GLERL was fully coupled with the Regional Atmosphere Modeling System (RAMS), a meso-scale meteorology model operationally used at ARL/NOAA. The sea state dependent over water sea surface roughness was fed back to the RAMS during the coupling processes. The GLERL predicted surface waves, RAMS predicted surface winds and heat fluxes were compared between the coupled/uncoupled runs and the data. It is found that fully coupled model runs can result in a significant difference between the GLERL predicted waves and RAMS predicted winds and heat fluxes. The surface wind waves play an important role in RAMS predictions of momentum and heat fluxes in the CB . The layout of the paper is as follows: In section 2, both GLERL and RAMS models are briefly described; The coupling procedure and results are presented in section 3; Summary and conclusion is given in section 4.

2. THE GLERL AND RAMS MODEL

2.1. *The GLERL model*

The GLERL wave model is a parametric, deep water numerical wave model. The model was developed by Donelan (1977) and used for wind wave forecasts in the Great Lakes (Schwab et al. 1984). Its basic equation is a local momentum balance equation. It is time dependent and can accommodate arbitrary wind and geography. Shallow water wave effects are not included, however. The wave energy spectrum $E(f)$ is assumed to follow the JONSWAP spectral shape (Hasselmann et al. 1973).

In the GLERL model, the total drag between air and water is treated as the sum of a skin friction (proportional to U_{n10}^2) and a form drag. The skin friction used in the model is defined as

$$\tau_s = \rho_a Cd_s U_{n10}^2, \tag{1}$$

where $Cd_s=0.7\times10^{-3}$ is the skin friction coefficient. The form drag of the wind over the waves, τ_f, is assumed to be proportional to the square of the relative velocity between wind velocity and wave phase velocity, such as

$$\tau_f = \rho_a D_f (U_{n10} - C)| U_{n10} - C |, \tag{2}$$

where C is wave phase velocity and D_f is the form drag coefficient given by

$$D_f = [\frac{\kappa}{\ln (10/z_0)}]^2. \tag{3}$$

The wave form drag changes with the development of waves, such that in a fully developed sea the dominant waves travel at phase speeds close to the driving wind velocity and τ_f becomes smaller and smaller. Full development corresponds to wave age, $C_p/U_{n10}=1.2$ (Donelan 1990). A relationship between the mean wave phase velocity, C, and peak wave phase velocity, C_p, was derived as $C_p/C=1.2$. Using this relationship

$$\tau_f = \rho_a D_f (U_{n10} - 0.83 C_p) \times | U_{n10} - 0.83 C_p |. \tag{4}$$

In the original model, $z_0 = \sigma/5$ was used where $\sigma^2=\int_0^\infty E(f)df$ is the variance of surface elevation. We tested this expression against the data and found that it predicted values of z_0 that were one to two orders of magnitude higher than

the observed surface roughness. We modified the model to calculate z_0 using a formulation by Donelan (1990), which explicitly accounts for the effect of wave age on surface roughness and agrees better with the data. The formulation is given by

$$\frac{z_0}{H_s} = 1.38\times10^{-4}\left(\frac{C_p}{Un_{10}}\right)^{-2.66}. \tag{5}$$

Finally, *Cd* is calculated as

$$Cd = \frac{\tau_f + \tau_s}{\rho_a U_{n10}^2}. \tag{6}$$

Estimated *Cd* is output based on the driving wind speeds and predicted wave conditions at each hour.

2.2. *The RAMS model*

The RAMS is a meso-scale meteorology model developed at Colorado State University (Pielke et al. 1992). ARL/NOAA uses the RAMS to predict transport and dispersion from radioactive releases. The RAMS and the other meteorology models such as ETA and RSM are used at ARL to support air quality emergency response forecasting. The RAMS is also evaluated for air pollution deposition into the CB. McQueen et al. (1994, 1997) summarized RAMS applications to create a meso-scale, real-time meteorological forecasts of surface winds and air-sea fluxes over the CB.

During its operation, the RAMS was initialized from National Center for Environmental Prediction (NCEP) model fields such as ETA, AVN, and NGM. Many surface variables such as soil moisture, soil and vegetation type, canopy temperature and water content, terrain height, land roughness, land percentage and sea surface temperature are ingested into the RAMS on the model grid. The over water surface roughness is given by (Valigura 1995)

$$z_o = \frac{0.016u_*^2}{g} + \frac{K}{9.1u_*}, \tag{7}$$

where K is the molecular diffusivity of heat. The first term on the right hand side of Eq. (7) is the standard Charnock (1955) formulation with a constant of $\alpha = 0.016$, and the second term corrects for the increasing roughness at very low wind speeds. The z_0 in Eq. (7) depends only on wind speed. It is replaced by the GLERL model predicted z_0 to include a sea state dependent surface roughness length in the coupling process.

The RAMS determines turbulent fluxes of heat, H, and moisture, LH, over water via the standard bulk-transfer coefficient equations

$$H = \rho_a c_p D_H U_z (T_0 - T_z), \tag{8}$$

$$LH = \rho_a L_W D_W U_z (q_0 - q_z), \tag{9}$$

where T is temperature, q is specific heat, L_W is the latent heat of vaporization for water, c_p is the specific heat of air and

D_w, D_H are transfer coefficients of heat and water. These transfer coefficients are in turn functions of surface roughness and atmospheric boundary layer stability (McQueen et al. 1994).

2.3. *The RAMS and GLERL modeling domain*

The RAMS was run operationally over the CB with a finest mesh of 4 km and 25 vertical levels. The total number of grid points covering the RAMS grid were 82×102. The area to be modeled was 296×376 km as shown in Fig. 1. The RAMS was run in both an assimilative and forecast mode.

The GLERL model domain is represented by horizontal grids, covering a rectangle domain. The modeled area was 128×308 km, which is in the RAMS grid (Fig. 1). The west-east direction was chosen as X direction with 321 grid points. The spacial spacing in X is equal to 400 m with a total length of 128 km. The south-north direction is chosen as Y direction with 771 grid points. The spatial spacing in Y is 400 m with a total length of 308 km.

A conformal Lambert Polar Conical projection (Taylor 1997) was used for the modeling domain. The latitude and longitude of the tangent point with both models was at (38.25, -76.5). The grid spacing was 4 km for RAMS and 400 m for GLERL, allowing RAMS grids to roughly match the GLERL grids every tenth grid. The central grids of RAMS was at (37, 47), matching the tangent point of (141, 401) in GLERL grids.

The GLERL was run in a UNIX system (DS20 DEC ALPHA) with 1,000 MHz EV6 CPU at HPL/UMCES. The execution time for one hour wind field ranged from one to several minutes, depending upon the maximum wind speed in the hour. The RAMS was run at an 8 processor (250 Mhz each) SGI Origin 2000 at ARL/NOAA. The output files from each model were transferred through the high speed network connection between HPL and ARL.

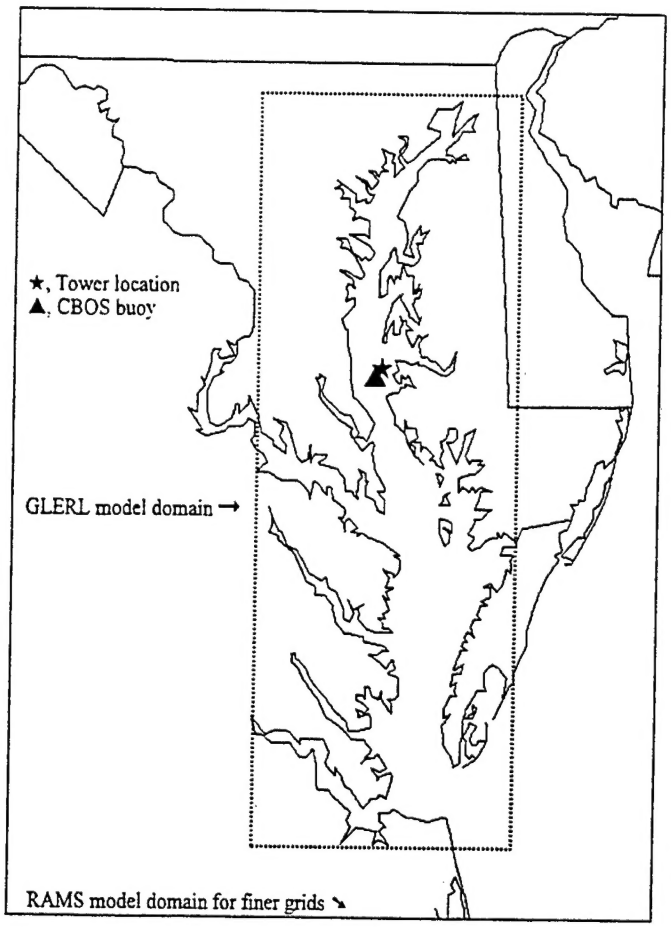

Fig. 1 The GLERL and RAMS (finer grids) model domain, and the tower and CBOS buoy location.

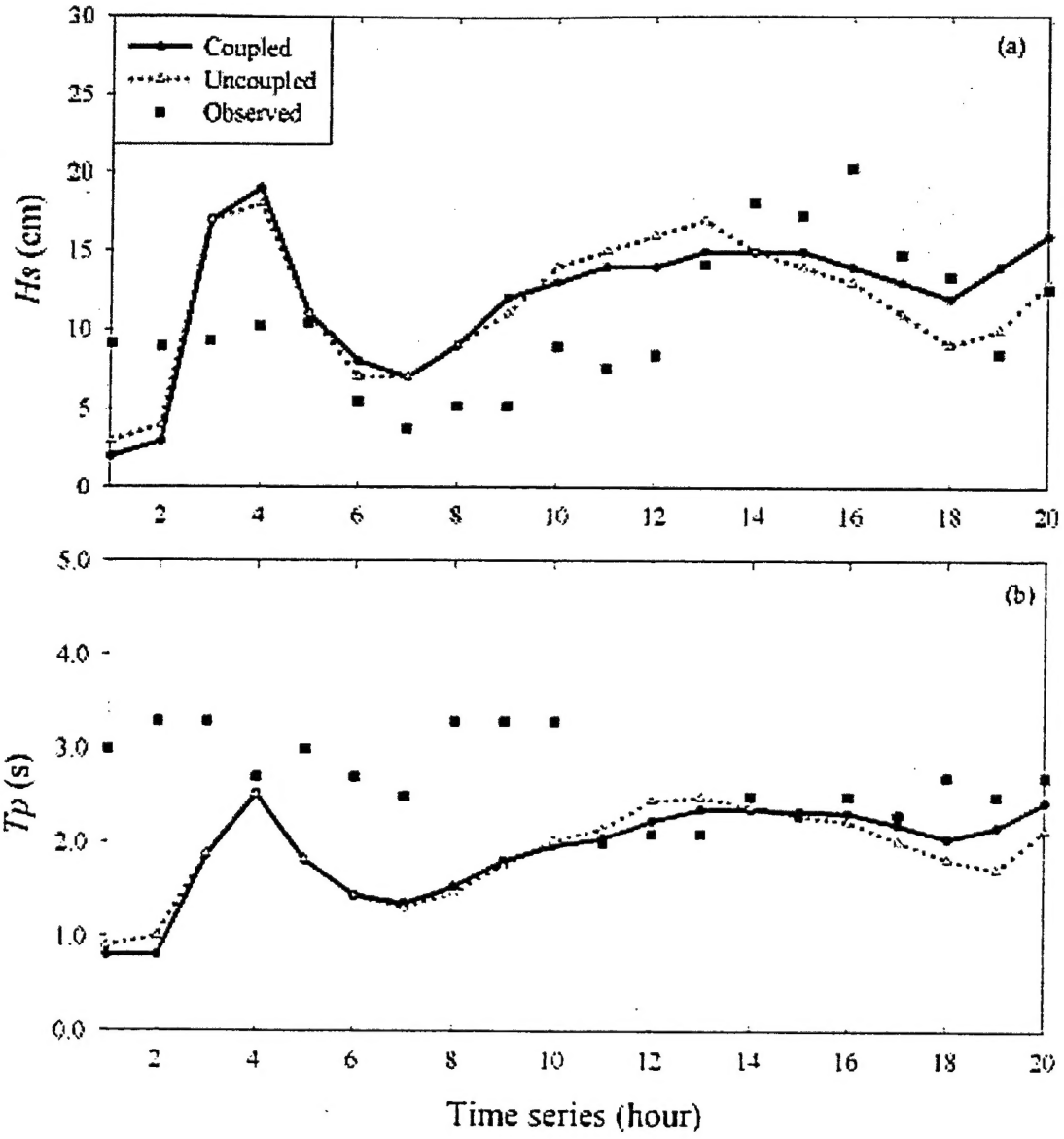

Fig. 2 A twenty hour time series of significant wave heights (a) and peak period (b) predicted by the coupled (solid line with open triangles) and uncoupled (dotted line with solid circles) GLERL model. The observed wave data at the tower location is shown by solid squares.

3. THE COUPLED MODEL RUNS AND RESULTS

3.1. *The uncoupled model runs*

Before the two models were coupled, the RAMS was run with a series of fourteen hour simulations. A two-day simulation was completed with a 4 ×14 hour simulation. The first two hour simulation was replaced by the last two hour simulation, reducing model spin-up of moisture wich occurred during the first three hour of a model simulation.

Following the procedure below, the uncoupled RAMS was run from 1200 UTC July 22 to 1200 UTC July 24.

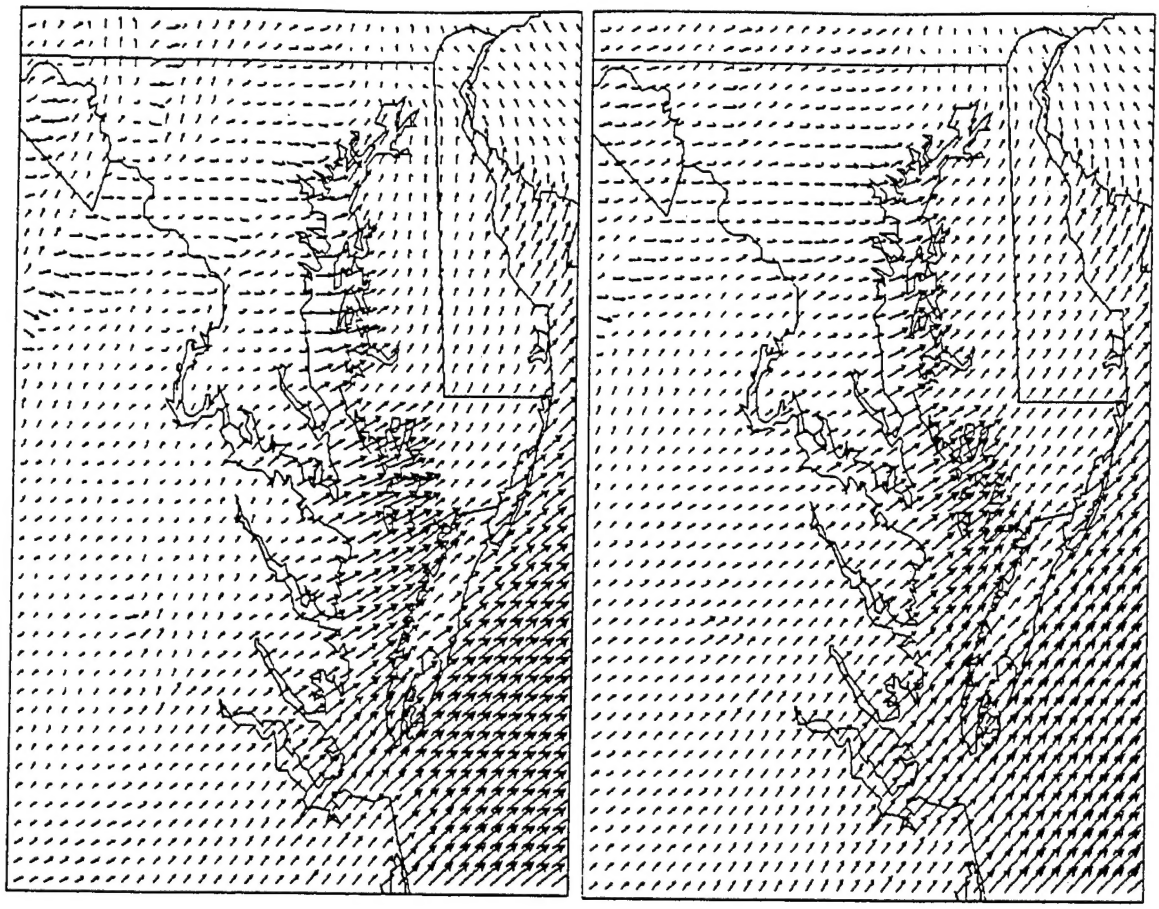

Fig. 3a Surface wind vectors predicted by uncoupled (left) and coupled (right) RAMS for 1100 UTC July 23, 1998. Vectors are drawn every tenth of RAMS finer grids.

Simulation 1: Hours +0 ~ +14 (1200 - 0200 UTC July 22)
Simulation 2: Hours +12 ~ +26 (0000 - 1400 UTC July 23)
Simulation 3: Hours +24 ~ +38 (1200 - 0200 UTC July 23)
Simulation 4: Hours +36 ~ +50 (0000 - 1400 UTC July 24)

At the beginning of each simulation, RAMS is initialized with ETA's 40 km fields in the east US. The RAMS is run at two different grid resolution: a coarser grid with 16×64 km resolution and a finer grid with 4×4 km grid resolution. The finer grid is nested in the coarser grids which are used to supply the boundary conditions. The coarser grid domain is much larger than the finer grid domain shown in Fig. 1. The RAMS was run twice for 0000, 0100, and 0200 UTC July 23: one for the first simulation and the other to complete a spin-up cycle for the next simulation. These four simulations were completed by repeating the procedure four times.

3.2. *The coupled GLERL/RAMS model runs*

The coupled GLERL/RAMS model runs started with the GLERL model. It was driven by the first hour uncoupled RAMS wind at 1200 UTC July 22. After z_0 was calculated in the GLERL at every 4 km grid, it was fed back to the RAMS and used as the first hour over water sea surface roughness for RAMS finer grid. Then the RAMS was

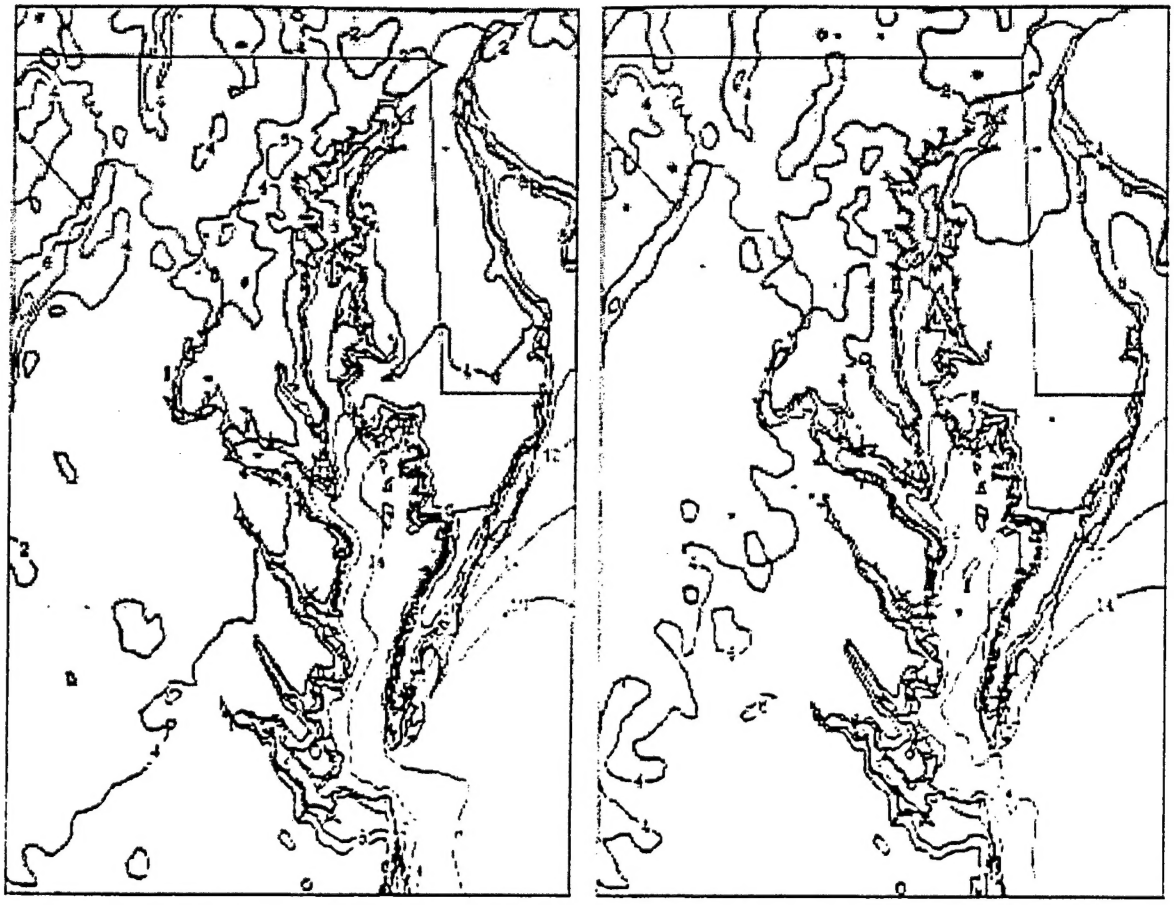

Fig. 3b Surface wind speed contour predicted by uncoupled (left) and coupled (right) RAMS for 1100 UTC July 23, 1998.

initialized with ETA's wind field. The RAMS was run at coarser grid first. The sea surface roughness over the very few water points in the coarser grid were calculated with Eq. (7). The RAMS finer grids used the output from coarser grid as boundary conditions. In RAMS finer grids, z_0 over land changed every time step at 15 s, but z_0 over water was exchanged with the wave model output at each hour. This is justified by the fact that wave condition does not change significantly within an hour period of time and the over water z_0 field can be considered as a constant. For the RAMS predicted 10 m height surface winds, stability was corrected with air and water temperature data from the Chesapeake Bay Observing System (CBOS) (see Fig. 1) and then used to drive the GLERL wave model for the next hour. The process was repeated 14 times to complete a twelve hour simulation.

3.3. *Results*

The coupled/uncoupled GLERL predicted surface wind waves are compared to the wave data at the tower location. A twenty hour time series model data comparison of significant wave height, *Hs*, and peak period, *Tp*, for the coupled and uncoupled model runs is given in Fig. 2. Fig. 2a shows that the significant wave heights predicted by coupled GLERL are in slightly better agreement with data than those predicted by uncoupled model runs. The predicted peak periods by the coupled wave model also show a slightly better agreement with data than those predicted by the uncoupled wave model runs, as shown in Fig. 2b. The large biases for both models at the beginning of the time period are probably due to the RAMS model spin-up.

The difference in *Hs* and *Tp* prediction between coupled and uncoupled GLELRL wave model is a result of

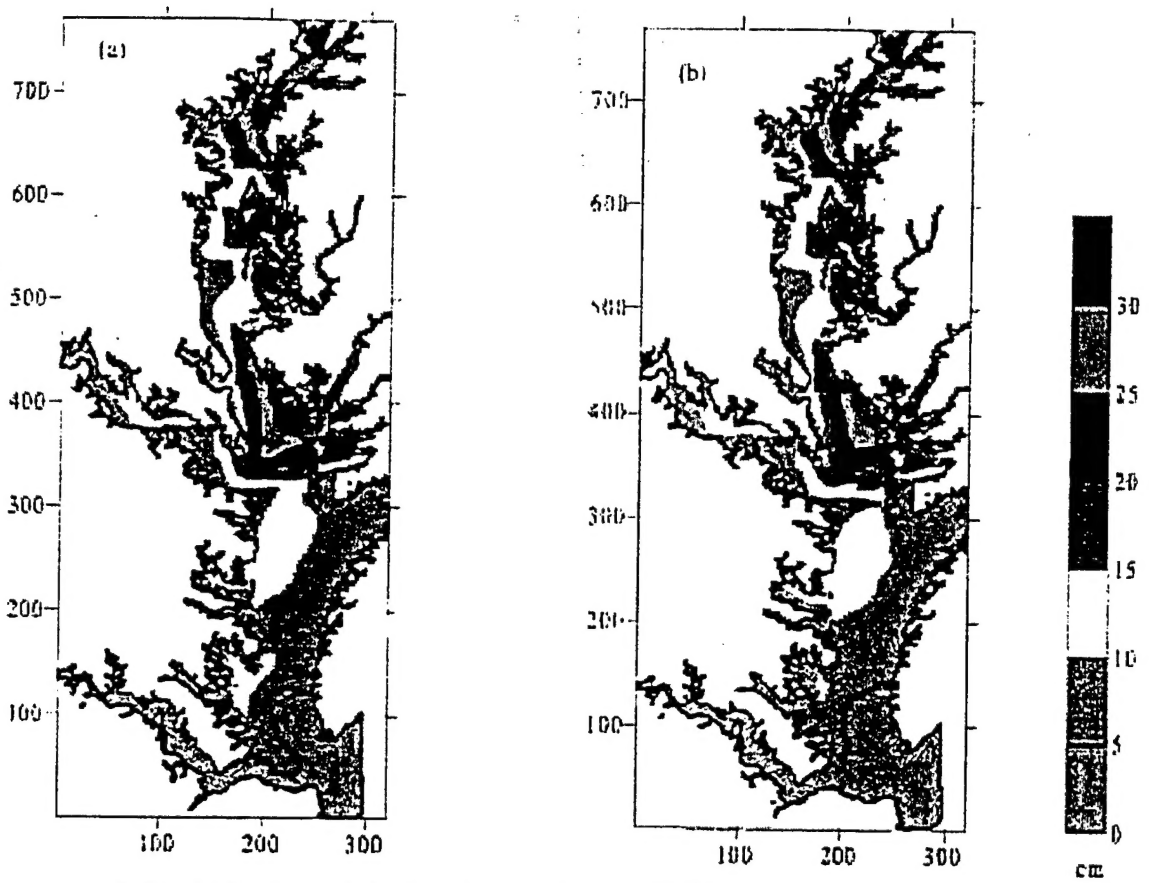

Fig. 4 The significant wave height (cm) field predicted by GLERL wave model. The wind field used is from uncoupled (a) and coupled (b) RAMS model for 1100 UTC July 23, 1998, which is shown in Fig. 3.

the difference between coupled and uncoupled RAMS predicted surface winds (speeds and direction). An example of RAMS predicted surface wind field over the CB for 1100 UTC July 23 is given in Fig. 3a&b for the uncoupled and coupled results. The vector plot in Fig. 3a shows wind direction and speed at every tenth of RAMS finer grids. Both wind vector plot (Fig. 3a) and contour line plot (Fig. 3b) are generated with READY (Realtime Environmental Applications and Display System at http://www.arl.noaa.gov/ready/cmet.html), a web based plotting tool developed at ARL/NOAA. Fig. 3 shows that the wind field predicted by coupled RAMS is smoother than the uncoupled wind field over most of the CB. There is a significant difference in the wind speed and direction in the mid-CB area, with wind speed predicted by the coupled RAMS lower than those predicted by the uncoupled RAMS for this hour.

The difference in the wind field predicted by uncoupled and coupled RAMS model results in a significant different wave heigh (Fig. 4) and peak period field (Fig. 5). Although *Hs* and *Tp* predicted by GLERL model with uncoupled and coupled RAMS wind field only show slightly difference at the tower location, there are significant differences for the distributions of *Hs* and *Tp* field. Fig. 4 shows that the GLERL predicted wave height is larger in the southern Bay, if the RAMS uncoupled wind field for 1100 UTC July 23 is used. The difference in peak period field for uncoupled (Fig. 5a) and coupled (Fig. 5b) RAMS wind field for the same time is also significant in southern Bay, with a higher *Tp* prediction by uncoupled wind field.

The sensible heat fluxes predicted by the uncoupled RAMS (Fig. 6a) and coupled RAMS (Fig. 6b) for 1100 UTC July 23 show a significant difference over both land and water in the entire RAMS domain. Sensible heat fluxes

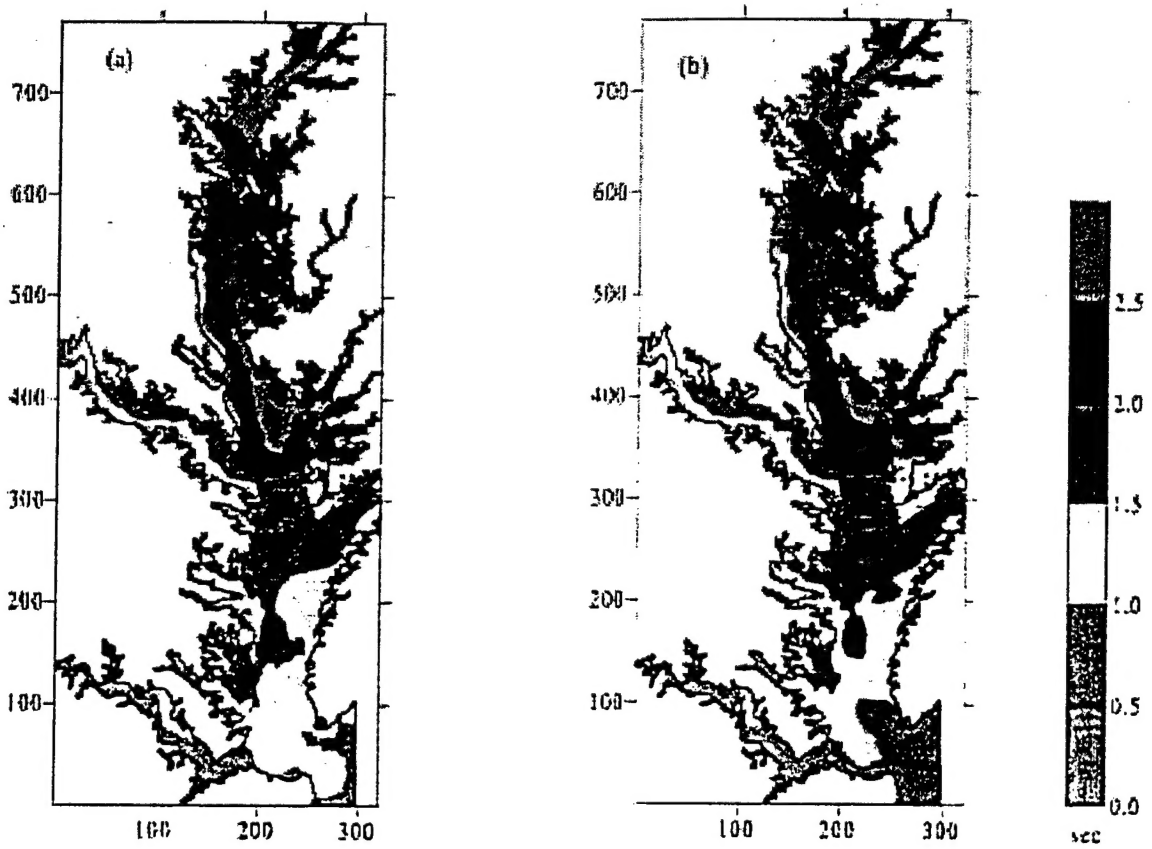

Fig. 5 The peak wave period field (s) predicted by GLERL wave model. The wind field used is from uncoupled (a) and coupled (b) RAMS model for 1100 UTC July 23, 1998, which is shown in Fig. 3.

from the coupled RAMS model in Fig. 6b have more spatial variations over water than the uncoupled model in Fig. 6a.

The latent heat fluxes predicted by the uncoupled RAMS in Fig. 7a is also significantly different from those predicted by the coupled RAMS in Fig. 7b. It is interesting to note that the difference occurs both over land and water, which is similar to the sensible heat fluxes in Fig. 6. Over land, there is a significant difference in both sensible and latent heat fluxes between the coupled and the uncoupled modeling results. Over water, the latent heat fluxes predicted by the coupled model runs in Fig. 7b are smaller than those predicted by uncoupled modeling results in the mid-Bay. However, the latent heat fluxes over the water at the Bay mouth are larger for the coupled model runs in Fig. 7b than those for the uncoupled model runs in Fig. 7a.

The heat fluxes predicted by coupled RAMS are significantly different from those predicted by uncoupled RAMS. This is partly due to the fact that the over water sea surface roughness length in the coupled runs has much more complicated spatial structures than the modified Charnock relationship in Eq. (7) which is previously used in the RAMS model. In the coupled runs, the sea state is a strong function of fetch and varies with the wind speeds and direction. For short fetch, a higher surface roughness is expected for young wind seas; for longer fetch, the surface roughness is relatively lower (Lin et al. 2002). The GLERL predicted sea state dependent sea surface roughness is fed back to the RAMS model during the coupling process. This may account for some of the difference between the coupled and uncoupled results. However, the present study can not explain all the differences between the coupled and uncoupled model runs. One possible explanation is that the RAMS model may be very sensitive to the changing of over water roughness. More coupled model tests are needed to address this issue.

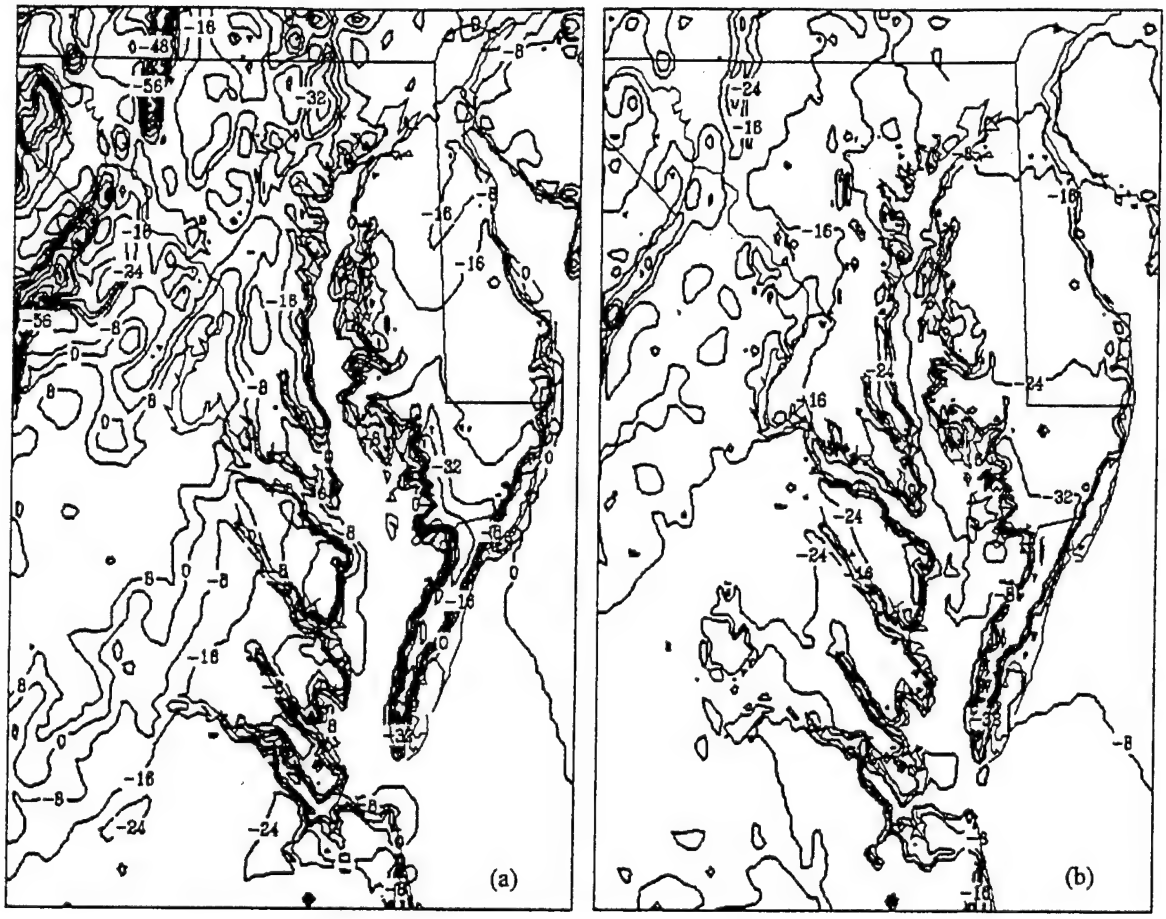

Fig. 6 Sensible heat fluxes predicted by the uncoupled (a) and coupled (b) RAMS model for 1100 UTC July 23, 1998.

4. SUMMARY AND CONCLUSIONS

In this study, surface wind wave effects on air-sea heat and momentum fluxes in the CB is investigated with a fully coupled GLERL/RAMS modeling test against a data set from a tower experiment. Comparisons are made among the coupled and uncoupled modeling results and the tower data. Through this study, it is found that in an entirely fetch limited coastal environment, *Hs* and *Tp* predicted by the coupled GLERL agree with the data slightly better than those predicted by the uncoupled model, if compared with data at the tower location. The difference results from the difference between the coupled and uncoupled RAMS wind field. The field distribution of *Hs* and *Tp* from coupled and uncoupled GLERL model also shows significant differences in the southern Bay.

Compared with uncoupled RAMS model, the coupled RAMS can predict a significant different wind field (both in wind speed and direction). The coupled model runs tended to give smoother spatial distribution of the wind field than the uncoupled model runs. In the mid-CB, the uncoupled RAMS predicted a higher wind speed than the coupled RAMS, and the wind directions are also different.

The sensible and latent heat fluxes predicted by RAMS model also show a significant difference between the coupled and uncoupled model runs. The difference occurs both over land and water, covering the entire RAMS domain. One obvious reason to account for this difference is the sea state dependent surface roughness that is fed back from

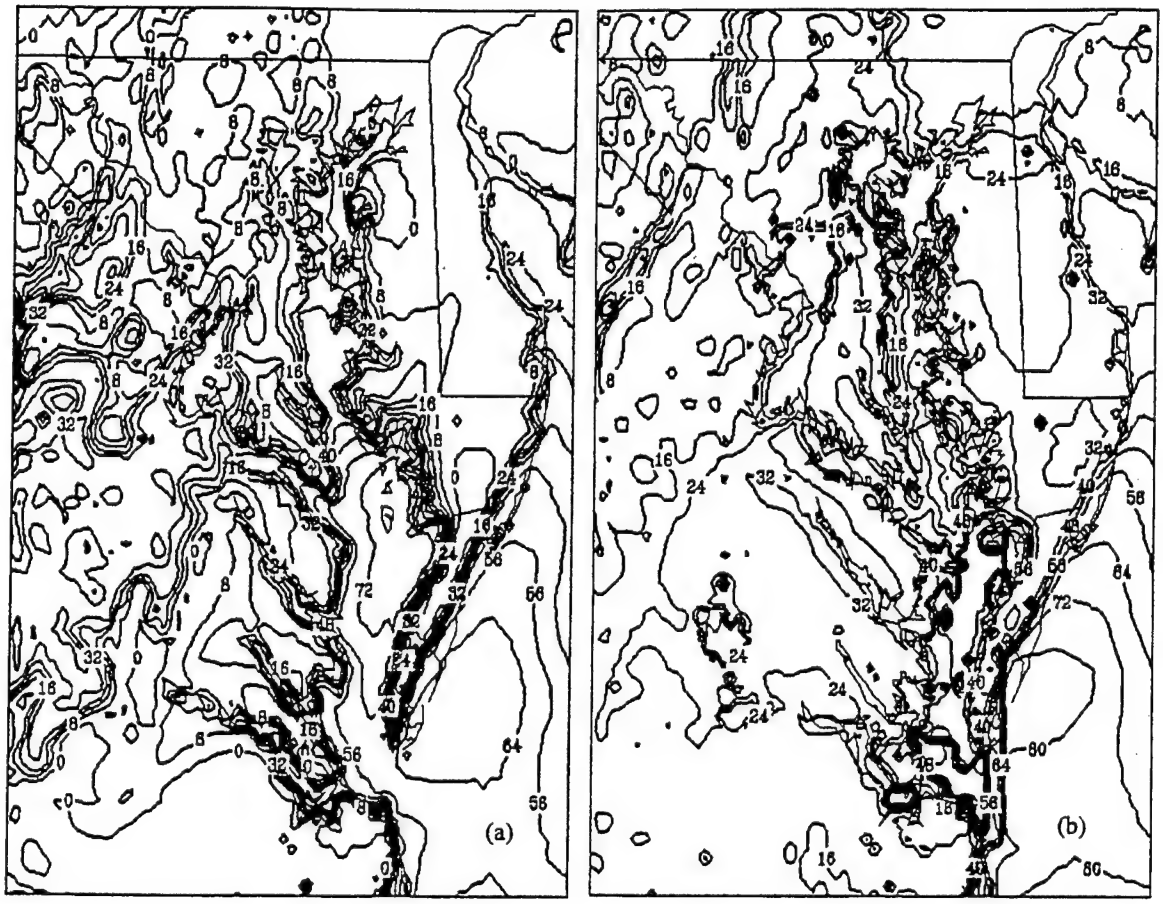

Fig. 7 Latent heat fluxes predicted by the uncoupled (a) and coupled (b) RAMS model for 1100 UTC July 23, 1998.

GLERL to RAMS during the coupling processes. However, the sea state dependent sea surface roughness does not explain all the difference in the heat flux predictions by the RAMS model, which implies that the RAMS model may be quite sensitive to changes in the sea surface roughness parameter.

From this study, we can conclude that the surface wind waves play an important role on the surface winds, sensible and latent heat fluxes in the CB, a fetch limited coastal environment with young wind seas dominate. The significant difference in the surface wind, heat flux prediction between the coupled and uncoupled GLERL/RAMS model shows that it is necessary to develop a coupled modeling system to include sea state dependent surface roughness in the RAMS model. Finally, we would like to point out that the current study does not answer two questions: one is the over water sea surface roughness in low winds; the other is the sensitivity of the RAMS model on the changing sea surface roughness. We would like to pursue more coupled modeling tests in the future to address these issues.

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